Chapter I:
Introduction and Summary

The tropical Pacific coupled ocean/atmosphere system exhibits large-scale variability on both the seasonal and interannual timescales. The primary mode of tropical Pacific interannual variability is related to the El Niño/Southern Oscillation (ENSO) phenomenon (Weare et al. 1976, Rasmusson and Carpenter 1982, Cane 1983, Harrison and Larkin 1996, 1998.a). The ENSO phenomenon is associated with large-scale changes on local biological productivity (Barber and Chavez 1983, Chavez *et al.* 1998) and global weather patterns (Donguy and Henin 1980, Rasmusson and Wallace 1983, Nicholls and Kariko 1993, Harrison and Larkin 1998.b). The air-sea interactions that bring about El Niño equatorial Pacific sea surface temperature (SST) changes are the focus of much interest at present (See the special issue of Journal of Geophysical Research (1998) for reviews on the range of recent El Niño research); understanding of these coupled mechanisms is essential to improving our understanding and prediction of El Niño. Ever since Wyrtki (1975) suggested that a collapse of the easterly trade winds led to the onset of El Niño warming, there has been interest in the types of atmospheric forcing that can cause this warming. I here examine the roles of two modes of sub-seasonal surface wind variability - the Madden-Julian Oscillation and westerly wind events - on the evolution of El Niño SST anomalies (SSTA).

Since Bjerknes (1961, 1966, 1969) suggested that the atmospheric circulation changes known as the Southern-Oscillation, and the central and eastern Pacific SST changes known as El Niño were fundamentally related, there has been much work in developing a dynamical framework to understand the two phenomena and their coupling. At present there are two main paradigms of the evolution of coupled ENSO system, one viewing the system as deterministic the other as fundamentally stochastic. One paradigm involves deterministic evolution of coupled ocean/atmosphere anomaly modes, as in the "Delayed-Oscillator" theory (*e.g.* Battisti 1988, Schopf and Suarez 1988 , Suarez and Schopf 1988, Battisti and Hirst 1989, Neelin *et al.* 1998) or the model of Cane and Zebiak (1985). The view that ENSO results from stochastic forcing in the tropical Pacific has been developed more recently (Penland and Magorian 1993, Penland and Sardeshmukh 1995, Penland *et al.* 1995, Thompson and Battisti 2000). There have been suggestions that seasonal and higher frequency wind variability, particularly "sub-seasonal" wind variability, is fundamental to the evolution of the ENSO cycle (Keen 1982, Lau and Chan 1986, 1988, Harrison and Giese 1988, Giese and Harrison 1990, 1991, Weickman 1991, Kessler *et al.* 1995, Harrison and Vecchi 1999, Moore and Kleeman 1999, Vecchi and Harrison 2000)

The spectrum of western and central equatorial Pacific surface winds is distinctive, with about half the zonal wind variability occurring in the sub-seasonal period band (Harrison and Luther 1990). Within the sub-seasonal band close to two thirds the variance is in periods between 3 and 30 days and about one third in periods between 30 and 90 days (Harrison and Luther 1990). At the high frequency end of the sub-seasonal band, pulses of equatorial westerly wind anomaly (westerly wind events or WWEs; Luther *et al.* 1983, Harrison and Giese 1991, Hartten 1996, Harrison and Vecchi 1997) have been suggested as a mechanism for the onset of El Niño waveguide warm anomalies. Ocean general circulation model (OGCM) experiments have suggested that equatorial WWEs can drive El Niño eastern and central equatorial Pacific SST changes (Harrison and Giese 1988, Giese and Harrison 1990, 1991).

It has also been suggested that 30-90 day surface wind variability in the western and central Pacific, driven by the Madden-Julian Oscillation (MJO; see Madden and Julian 1994 for a review), may be important to the onset of waveguide SST warming during El Niño (Lau and Chan 1986, 1988, Lau and Shen 1988, Weickman 1991, Kessler *et al.* 1995, Moore and Kleeman 1999). The MJO is the dominant mode of sub-seasonal tropospheric wind variability over the tropical Indian and Pacific oceans, having a characteristic eastward propagating signal in free-tropospheric winds and convection (e.g. Madden and Julian, 1972, 1994, Rui and Wang 1991, Hendon and Salby 1994, Maloney and Hartmann 1998). Interestingly, no correlation has been found between MJO activity indicators and El Niño indices (Slingo et al. 1999, Hendon *et al.* 2000, Harrison and Vecchi 2000).

The air-sea interactions which bring about the termination of El Niño are also of interest. Prior to the return of SST to normal at the end of recent El Niño events, there has been a shoaling of the eastern equatorial Pacific thermocline to normal or shallower than normal depths (Harrison et al. 1990, Kessler and McPhaden 1995, Harrison and Vecchi 1999, 2000, McPhaden 1999, McPhaden and Yu 1999). This thermocline shoaling might be due to “delayed-oscillator” type mechanisms (see Suarez and Schopf 1988, Battisti and Hirst 1989, Neelin et al. 1998), or to the interaction of the seasonal cycle with anomalous El Niño conditions (Harrison and Vecchi 1999), or a combined effect of the two. The shoaling of the thermocline at the end of recent El Niño events pre-conditioned the termination of El Niño, by making cool water available to be upwelled into the surface layer by equatorial easterly winds (Harrison et al. 1990, Kessler and McPhaden 1995, McPhaden 1999, McPhaden and Yu 1999). In weak El Niño events, such as 1986-8 and 1991-2, weakened easterly trades were present through the event; these easterly winds quickly cool the surface once the thermocline shoals and makes the cool water available (Kessler and McPhaden 1995). In strong El Niño events, such as 1982-3 and 1997-8, the easterly trades completely disappear; though the thermocline has shoaled for months, the surface does not cool until the return of easterlies of enough strength to upwell the cool water (Harrison et al. 1990, McPhaden 1999, McPhaden and Yu 1999, Takayabu et al. 1999). Takayabu et al. (1999) suggest that easterly winds in the eastern and central Pacific, driven by the passage of an MJO event in May 1998, resulted in the termination of the 1997-8 El Niño event.

In the chapters that follow I examine the role of sub-seasonal wind variability in the evolution of El Niño. I develop the roles of WWEs and the MJO on the evolution of El Niño

SSTA changes by: examining the surface wind structure of the two phenomena, analyzing statistical relationships to test recent suggestions that WWEs are the surface expression of the MJO, exploring the relationships the phenomena exhibit with El Niño waveguide warming, and finally by forcing an OGCM with the characteristic zonal stress fields of equatorial WWEs and the MJO to determine mechanisms for their role in El Niño.

In Chapter II, I examine the surface wind (x,y,t) structure of WWEs using a compositing technique, and the European Centre for Medium Range Weather Forecasts (ECMWF) 12-hourly gridded operational surface wind analysis (ECMWF 1989). I also examine the seasonal and inter-annual distribution of WWEs, and some relationships of WWEs to each other. I am able to classify WWEs into eight types based on the location of the maximum surface westerly wind anomalies, and derive a quantitative definition for a WWE based on the classifying scheme. Using the classifying scheme, I generate composites of surface wind anomaly for each of the WWE types, and find that the zonal wind anomalies of each type are compact in space and time, exhibiting little translation during the lifetime of the event. I model the WWE zonal wind anomaly field using a Gaussian structure in space and time, and derive characteristic scales for each event. WWEs have an average duration between 5.5 and 7 days, an average zonal width of roughly 30° longitude, and an average meridional width close to 10°. Equatorial WWEs display a statistically significant inter-annual correlation with the Troup Southern Oscillation Index (normalized sea level pressure difference at Darwin minus Tahiti; Troup-SOI), adding to the suggestion of a relationship between equatorial WWE types and El Niño.

In Chapter III, I build upon the WWE identification scheme developed in Chapter II, and use a compositing technique to examine the evolution of SSTA following equatorial WWEs. I begin by examining the evolution of SSTA in the absence of WWEs, and find that, in the absence of equatorial WWEs, tropical Pacific SST tends towards climatology. I examine the evolution of SSTA following WWEs separately for periods of warm eastern equatorial Pacific SST and periods of near-normal eastern equatorial Pacific SST. Following equatorial WWEs, the eastern equatorial Pacific SST tends to warm (when SST initially close to climatology) or tends to remain warmer than normal (when ST initially warmer than normal). These results suggest that equatorial WWEs are a fundamental mechanism for El Niño warming and maintenance.

In Chapter IV, I explore the convective and surface wind anomaly fields associated with WWEs and with the MJO. The composite wind anomaly fields associated with the MJO do not much resemble the idealized structures generally used to discuss their role in ENSO. The MJO surface wind anomaly field in the equatorial Pacific extend beyond the convective regime over the western Pacific warm pool. Models of the role of the MJO in El Niño waveguide warming developed using anomalies confined to the western equatorial Pacific are not consistent with these composite results.

WWEs tend to be convective features, however they do not resemble any single atmospheric mode of variability. WWEs of most types which occur during the MJO are modulated by the convective variability associated with the MJO. Less than half of all WWEs occur during the westerly phases of the MJO, and many MJO events do not have any WWEs associated with them. Tropical cyclones are strongly associated with west-of-dateline WWEs: the westernmost WWE Types (those west of 150°E) are associated with tropical cyclones over 90% of the time, the WWE Types occurring between the Dateline and 150°W are associated with tropical cyclones over 60% of the time.WWEs are associated with a variety of large-scale circulation structures, and are not the surface expression of any one mode of atmospheric variability.

In Chapter V, I use an OGCM to attempt to and reproduce the statistical associations between sub-seasonal surface wind variability and tropical Pacific SSTA. The composite MJO developed here does not provide a mechanism for equatorial Pacific waveguide warming in the onset of El Niño events. Because the MJO is associated with both easterlies and westerlies, it provides a potential mechanism for the return of normal SST at the end of major El Niño events (such as 1982-3 and 1997-8).

Experiments using the realistic zonal scales of WWEs qualitatively reproduce the results of Harrison and Giese (1988) and Giese and Harrison (1990,1991). Multiple WWEs reproduce much of the composite SSTA changes following WWEs; individual WWEs do not reproduce the composite SSTA changes. Sequential equatorial WWEs provide a mechanism for the onset and maintenance of El Niño. The OGCM, without atmospheric coupling, is unable to reproduce the aplitude of the composite SSTA changes following WWEs.

Sub-seasonal surface zonal wind variability over the tropical Pacific is a component of the ocean/atmosphere interactions which bring about El Niño SSTA changes. Equatorial WWEs are been a mechanism for the onset and maintenance of warm El Niño SST. Central and eastern equatorial Pacific zonal wind variability related to the MJO provides a mechanism for the return of SST to normal at the end of major El Niño events. Improved understanding of the various modes of sub-seasonal wind variability, including WWEs, the MJO, tropical cyclones, mid-latitude cold surges and convective super-clusters, and of the interactions between these modes of sub-seasonal variability and the tropical Pacific circulation, will lead to improved understanding and predictability of the ENSO cycle.